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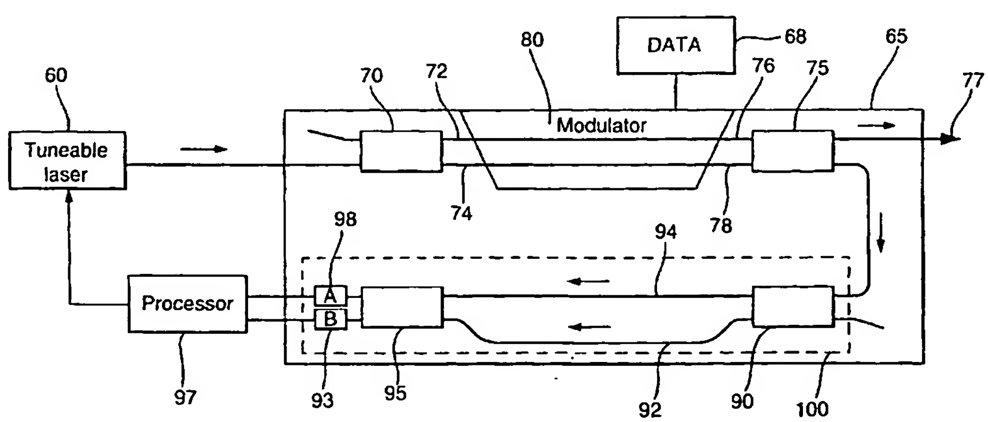

(57) Abstract: A wavelength locker (100) for use with a tuneable laser (60) capable of selectively producing light of fixed wavelengths, said fixed wavelengths having a substantially fixed wavelength spacing; the locker for locking the wavelength of the light to one of said fixed wavelengths and comprises: an interferometer arrangement comprising splitting means (90) for splitting the laser light to pass along two optical waveguides (92, 94) and combining means (95) for combining light from the waveguides to form at least one optical output (93, 98); wherein the optical waveguides are configured to have a difference in optical path length such that the magnitude of the at least one optical output varies cyclically with wavelength and has a waveguide period which is substantially an integer multiple of said fixed wavelength spacing; and control means (97) for controlling the laser in response to the magnitude of said optical output to lock the laser to one of said selected fixed wavelengths.

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WAVELENGTH LOCKER

This invention relates to a wavelength locker for use with a tuneable laser for locking its light output to a selected wavelength. More especially, although not exclusively, the invention concerns a wavelength locker for use within a wavelength division multiplex (WDM) optical communication system for locking the laser to a selected WDM wavelength channel.

In an optical fibre communications system, which utilises light of a single wavelength, the specific wavelength of the laser source is not critical provided it falls within the low insertion/dispersion characteristics of the optical fibre and the response bandwidth of the receiver. Provided the response of the receiver is broad enough it will still be able to detect the modulated optical signal even if the source laser wavelength should drift or vary for any reason.

The causes of laser wavelength variation are dependent upon operating temperature, the physical construction of the laser, and the ageing characteristics of the materials used to fabricate the laser. For example a distributed feedback (DFB) laser will shift around 0.1nm per °C temperature change i.e. of the order of 10GHz per °C, in the 1550nm communications band. For this reason laser sources are often provided with sophisticated temperature controllers.

To increase the information carrying capability of optical fibre communications systems wavelength division multiplex (WDM) systems are being developed in which a number

of different wavelengths often termed wavelength channels, are carried over a single optical fibre. In WDM systems drift of the wavelength channels limits the number and spacing of the channels and hence the data carrying capacity of the system.

As is known there are two principal communications wavelength bands 1300nm, and 1550nm. The latter band is receiving the greater commercial exploitation because of its suitability for a variety of different generic communications applications. Currently 1550nm WDM communications systems are rapidly evolving into architectures comprising 80, 2.5Gb/s modulated wavelength channels on a single fibre. The same 1550nm band is also being proposed for 40, 10Gb/s channels thereby doubling the fibre information capacity.

The 1550nm optical fibre communication band is located in the Infra Red spectrum with ITU (International Telecommunication Union) 200, 100 or 50GHz channel spacing (the so-called ITU grid) spread between 191THz and 197THz. The operating life ITU channel wavelength stability specification for telecommunication systems is typically set at 10pm. This corresponds to 1.25GHz variation (in the 1550nm band) over the system operating life.

To provide 40 or 80 individual wavelength circuits within the 1550nm band requires a light source that can be accurately set to specific wavelengths and maintained at these wavelengths, within specified limits, over the equipment operating life. Such light sources historically comprise a plurality of distributed Bragg reflector (DBR) lasers each of which is operated to produce light of one of the wavelength channels and optical

switching means for selecting a required wavelength channel. Whilst such an arrangement is effective it is impracticable for more than ten or so wavelength channels.

To overcome this problem wide tuning range lasers are being developed such as the sample grating distributed Bragg reflector (SGDBR) laser as described in A M Gulisano, D J Robbins, P J Williams, and P Verhoeve (1997) "Widely Tuneable Sampled Grating DBR Lasers to address 100 channels over 40nm for WDM applications", Proc. Euro. Conf. on Int. Optics. The tuning mechanism of the SGDBR laser is by differential current steering of the operating wavelength by means of the currents injected into the front and rear sample grating Bragg reflector sections, with fine tuning (trimming) being possible by means of current control in the phase section.

As discussed, if uncorrected, a solid state laser's wavelength will vary and this calls for a mechanism to stabilise and lock the wavelength of operation to a selected wavelength – so called wavelength locking. Whilst many solid-state lasers are provided with temperature stabilisation this is not sufficient to hold the wavelength of operation to the required accuracy for WDM and the future high density WDM or ultra high density WDM systems.

One known method of wavelength locking utilises a Fabry-Perot filter (etalon) to accurately measure the wavelength and to fine-tune the laser in a feedback arrangement. An example of such an arrangement is given in US 5,825,792 which utilises a Fabry-Perot filter having a cavity defined by planes which are angled to each other to provide the wavelength discrimination function. Although such wavelength lockers are effective

the physical construction of the etalon, two mirrors which are accurately spaced apart, is incompatible with integrating the filter with the solid state laser. The present invention has arisen in an endeavour to provide a wavelength locker that, at least in part, alleviates the limitations of the known arrangements.

According to the present invention a wavelength locker for use with a tuneable laser capable of selectively producing light of fixed wavelengths, said fixed wavelengths having a substantially fixed wavelength spacing; the locker for locking the wavelength of the light to one of said fixed wavelengths and comprises: an interferometer arrangement comprising splitting means for splitting the laser light to pass along two optical waveguides and combining means for combining light from the waveguides to form at least one optical output; wherein the optical waveguides are configured to have a difference in optical path length such that the magnitude of the at least one optical output varies cyclically with wavelength and has a waveguide period which is substantially an integer multiple of said fixed wavelength spacing; and control means for controlling the laser in response to the magnitude of said optical output to lock the laser to one of said selected fixed wavelengths.

Preferably the locker further comprises means for changing the refractive index of one waveguide relative to the other to change the optical path length difference to set the optical path difference to be the integer multiple of the wavelength spacing.

Alternatively the means for changing the refractive index is operable to set the optical path difference such that the laser locks to a wavelength which is offset by a selected amount from one of said wavelengths.

Advantageously the wavelength locker further comprises temperature sensing means for measuring the temperature of the waveguides and wherein the means for changing the refractive index operates in dependence on the measured temperature to maintain the optical path length difference constant.

In a preferred implementation the optical waveguides comprise an electro-optic material, preferably a group III-V semiconductor material such as gallium arsenide and the means for changing the refractive index comprises one or more electrodes associated with the, or each, waveguide. Preferably the waveguides are formed by a multi-layered structure and defined by a rib loaded structure and the one or more electrodes are provided on the rib structure.

The magnitude of the at least one optical output is sensed using an optical to electrical converter, such as for example a photodiode which can be a discrete device or monolithically integrated as part of the interferometer. In a preferred implementation the optical to electrical converter senses the magnitude of the at least one optical output by measuring a photocurrent generated by two photon absorption.

Preferably the wavelength locker further comprises a second interferometer arrangement whose optical path length difference is selected such that the magnitude of its optical output varies cyclically with wavelength and wherein the period is substantially twice the wavelength range and wherein the magnitude is used to provide

an indication of the wavelength. Such an arrangement not only ensures that the laser is locked to one of the fixed wavelengths but also gives a indication of the wavelength.

Advantageously the splitting and/or combining means comprises a directional coupler or multimode interference device.

Preferably the, or each, interferometer arrangement comprises an unbalanced Mach-Zehnder. Most preferably the, or each, interferometer is fabricated in a group III-V semiconductor material most preferably gallium arsenide.

Advantageously the combining means produces complementary optical outputs and the control means controls the laser in response to the magnitude of said optical outputs. In one arrangement the control means are configured such that when the magnitude of the optical outputs are respectively a maximum and minimum this indicates that the wavelength is locked to one of said fixed wavelengths. Alternatively it can be configured such that when the magnitude of the optical outputs are complimentary, for example both substantially zero, this indicates that the wavelength is locked to one of said fixed wavelengths. Any alternative output conditions can be used to determine wavelength lock.

Due to the wavelength locker of the present invention being based on an interferometer arrangement it readily lends itself to being monolithically integrated with the laser. Preferably the wavelength locker further comprises monolithically integrating an optical modulator for modulating the laser light. The modulator can be located at the laser

output or at the output of the interferometer arrangement. The wavelength locker of the present invention can also be fabricated as part of a micro-optical assembly.

Preferably the fixed wavelengths are wavelength division multiplex channels. Advantageously the wavelength locker is further operable to detect incipient wavelength mode jumps of the laser and further configured upon detecting a mode jump to tune and lock the laser to an alternative wavelength.

In order that the invention is better understood a wavelength locker in accordance with the invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 a schematic representation of unbalanced Mach-Zehnder interferometer;

Figure 2 a plot of optical output versus relative phase shift for the interferometer of Figure 1;

Figure 3 a schematic representation of a tuneable unbalanced Mach-Zehnder interferometer as used as a wavelength locker of the present invention;

Figure 4 a plot of optical output versus wavelength for the interferometer of Figure 3;

Figure 5 a further plot of output versus wavelength for the interferometer of Figure 3;

Figure 6 a schematic representation of wavelength locker in accordance with the invention;

Figure 7 an interferometer as used in the wavelength locker of Figure 6;

Figure 8 is a calibration arrangement for the wavelength locker of Figure 6;

Figure 9 a laser transmitter incorporating a wavelength locker in accordance with the invention;

Figure 10 a schematic representation of a further wavelength locker in accordance with the invention, which additionally incorporates means for measuring the wavelength;

Figure 11 a plot of optical output (intensity) versus wavelength for the wavelength locker of Figure 10;

Figure 12 a dense wavelength division multiplex optical communication system incorporating wavelength lockers in accordance with the invention; and

Figure 13. a tuneable laser transmitter incorporating a wavelength locker in accordance with the invention which can lock to network WDM wavelength channels.

The wavelength locker of the present invention makes use of an unbalanced optical interferometer as a wavelength discriminator. Figure 1 is a schematic representation of an unbalanced Mach-Zehnder optical interferometer. As is known a Mach-Zehnder interferometer comprises splitting means 10 for dividing input light 5 equally between two optical waveguide paths 15, 20 and combining means 30 for combining light from the waveguides to form two optical waveguide outputs 35, 40. Typically the splitting and combining means comprise directional couplers which operate by optical coupling between the waveguides when they located in close proximity to each other. The length of the waveguide sections over which coupling takes place is selected such that equal light power division between the two waveguides occur.

For an unbalanced interferometer the optical path lengths of the two waveguides 15, 20 are unequal such that a relative phase shift ($\delta\varphi$) 25 is introduced to light travelling along the waveguides. Typically the relative phase shift is introduced by making the waveguide 15, 20 of different lengths. The distribution of light between the two output optical waveguides 35, 40 is a sinusoidal function of the relative phase $\delta\varphi$ introduced between the two optical waveguides 15, 20. The division of output light between waveguides 35, 40 is a cosine-squared function of the relative phase difference $\delta\varphi$. If optical to electrical converters (detectors) 50, 55 are placed to monitor the respective light outputs from waveguides 35, 40 then their outputs would have the form shown in

Figure 2. when plotted as a function of the relative phase shift $\delta\varphi$. The distribution of the light between the waveguide outputs is a sinusoidal function of the relative phase introduced between the two optical waveguides.

As is known group III - V semiconductor materials such as gallium arsenide are electro-optic in nature, that is its relative refractive index is dependent upon an applied electrical field. Thus in an interferometer of the type described the optical path length difference can be electrically tuned by changing the refractive index of one arm relative to that of the other. The amount of tuning is, however, in practical applications limited to a refractive index change of a fraction of 1%. A more useful wavelength sensitivity results when the two interferometer arms are made to differ in physical length by an amount δL which can readily be many wavelengths.

Figure 3. schematically shows an optical interferometer constructed in a group III - V material such as gallium arsenide, being of the type described, in which the waveguide 15 is of length $L+\delta L$ and the waveguide 20 of length L. Fine tuning of the optical path length difference ($n\delta L$) is achieved by application of a voltage to electrode 16 which acts upon the longer waveguide 15. The outputs A, B as detected by detectors 50, 55 respectively are substantially a sinusoidal function of optical wavelength with a null at A corresponding to a peak at B and vice-versa. The wavelength change to move from null to peak, $\delta\lambda$, is given by: -

$$\delta\lambda = \lambda^2 / (2.n.\delta L) \qquad (1)$$

where n is the waveguide effective refractive index of the waveguiding medium and λ is the mean wavelength of concern. The phase imbalance $\delta\varphi$ is given by: -

$$\delta\varphi = (2\pi.\delta L.(n+\delta n)) / \lambda \qquad (2)$$

where δn is the change in refractive index.

Thus it will be appreciated that the application of voltage to the electrode 16 allows the sinusoidal response to be translated along the wavelength scale as illustrated in Figure 4. Since the outputs A, B are complementary this enables the tuneable interferometer to be used to discriminate between wavelengths at its output as shown in Figure 4.

In accordance with the present invention the interferometer of Figure 3 is configured to have a response as shown in Figure 5 in which the wavelength period, $\Delta\lambda = 2.\delta\lambda = \lambda^2 / (n.\delta L)$, between successive features, most typically this will be between successive peaks or troughs, is selected to correspond to substantially the wavelength spacing between the fixed wavelengths it is intended to operate the locker with. Preferably the wavelength period is set to the ITU WDM wavelength channel separations of 200 or 100 or 50 GHz.

It will be appreciated that the wavelength period $\Delta\lambda$ is, for a given optical path length difference, dependent on wavelength and therefore the interferometer response cannot be precisely matched to the WDM grid for all the wavelength channels. In practice, however, the variation of the wavelength period over the entire wavelength range of the WDM grid is found not to substantially affect the performance of the wavelength

locker. For example for C band, 1530 to 1560nm, the variation of wavelength period is only 1 to 2%. To minimise the effects of this variation it is preferred to set the average wavelength period to correspond with ITU grid spacing. In the context of this patent application the term "wavelength period" is the wavelength interval between successive features of the interferometers cyclic response and as such it is not of constant value.

It will be appreciated that such an interferometer can then be used to detect when the input light drifts off of one of the ITU wavelength channels by detecting a decrease in the magnitude of A and/or the corresponding increase in the magnitude of B, or vice versa. By using this detected output in a feedback arrangement to control the wavelength of operation of the light source the wavelength of the light source can be locked to a selected wavelength and as such is a wavelength locker. Such an arrangement is shown in Figure 6.

Figure 6. shows a tuneable laser 60, such as a SGDBR laser, injecting light into a micro-optical photonic modulator sub-assembly 65 comprising a directional coupler 70 coupled to waveguides 72, 74 which are used to phase modulate the light in accordance to data from an information source 68. The phase modulated optical signals from the waveguides 76, 78 are fed into a directional coupler 75 to form intensity modulated outputs. One output of the directional coupler 75 provides the transmitter output 77. The second output of the directional coupler 75 is applied the directional coupler 90 of a wavelength locker 100. The outputs of the directional coupler 90 feed unbalanced optical waveguides 92, 94 which in turn feed into a directional coupler 95 whose

complementary outputs feed intensity detectors 98, 93. Elements 90, 92, 94, 95, 93 and 98 are an unbalanced Mach-Zehnder interferometer, which operates as a wavelength discriminator/locker. The outputs of detectors 93, 98 are fed to a processor 97 that assesses the relative intensities of the light detected and in response provides a control signal to steer the tuneable laser 60 back onto wavelength when it drifts. In an alternative arrangement the light fed into the wavelength locker 100 can be coupled directly from the laser 60. The laser 60, modulator 80 and wavelength locker 100 are preferably monolithically integrated onto a single substrate. The detectors 93, 98 can be either included in the monolithic optical integrated circuit or external thereto. In a preferred arrangement the detectors 93, 98 measure the intensity of light by measuring a photocurrent generated by two photo absorption enabling them to be readily integrated within the circuit. Alternatively discrete photo-diodes or a dual detector chip could be used.

As described above the free spectral range of the interferometer is configured to equal the WDM wavelength channel separation by configuring the optical path difference between the optical waveguides to correspond to an integer multiple of the wavelength separation. In operation the laser is controlled in response to the two outputs 93, 98 by operating at the quadrature (equal brightness) point(s) E, or the peak and trough point(s) on T-T, of Figure 5. Any alternative condition of one, or both, outputs can be used to indicate the wavelength lock condition.

Whilst the wavelength locker of the present invention provides a means of locking the transmitter to an ITU channel at the chosen channel spacing, it will still be prone to the effects of temperature variation.

The thermal sensitivity of a micro-optical photonic sub-assembly such as 65 of Figure 6, is due to change in group refractive index with temperature. The refractive index of gallium arsenide is relatively high being typically in the range 3.3 to 4.3 compared to typical glass values used in optical fibre of 1.3 to 1.5. Thus the values of δL and $\delta\varphi$ derived in equations (1) and (2) are very sensitive to temperature since the group refractive index will vary with temperature. Achieving the target source laser wavelength stability of a few 10's of pico-metres would require temperature control of the micro-optical photonic sub-assembly incorporating the wavelength locker, to a few 1/10ths of a degree C.

To overcome this problem a further wavelength locker in accordance with the invention which incorporates temperature compensation is shown in Figure 7. As can be seen from this figure the optical waveguides of the interferometer are furnished with contacts such that an electrical bias can be applied relative to a common bias electrode. For clarity in Figure 7 only the wavelength locker section 100 of Figure 6 is shown with the incorporation of correction electrodes 102, 104, and 106. In Figure 7 like reference numerals denote elements which are functionally equivalent to those of Figure 6 save that there is shown diagrammatically the common bias electrode 102 against which biasing of the waveguides 92 and 94 via electrodes 106 and 104 may take place, in order that the group refractive index can be changed thereby tuning the effective

waveguide optical lengths. The electrodes 102, 104 and 106 would typically be fabricated as aluminium on top of a thin titanium bonding layer (Ti:Al) with 104 and 106 on top of a rib waveguide structure. It is an advantage to make the electrodes long, even though the path difference will only be around 500μm. Typically the common bias electrode 102 will comprise the substrate metalisation when the interferometer is monolithically fabricated as an integrated optical circuit

In the case of a wavelength locker shown in Figure 3 the directional coupler 10 - used as a splitter, and the directional coupler 30 - used as a combiner, have the same phase characteristics. If we seek to differentiate between a desired wavelength λ_1, and some arbitrary second wavelength λ_2, then for a particular path length δL, and the in-phase path:

$$(2.\pi.n_1.\delta L) / \lambda_1 = 2.\ p.\pi \qquad (3)$$

and for the out of phase path

$$(2.\pi.n_2.\delta L) / \lambda_2 = 2.(q-1/2).\pi \qquad (4)$$

where p and q are integers, and n_1 and n_2 are the respective refractive indices. Therefore $\delta L = p.\lambda_1/n_1 = (q-1/2).\lambda_2/n_2$. For the situation of n_1 and n_2 being a small difference then $p.\lambda_1 = (q-1/2)\ .\lambda_2$. The spacing between the ITU wavelengths on a 200 GHz grid is approximately 1.6nm. Thus if λ_1 is 1550nm and λ_2 is 1551.6nm then the lowest values p and q could be are p = q = 484 (for a 100 GHz grid spacing p = q = 969,

and for a 50GHz spacing p = q = 1938). For a typical GaAs refractive index of 3.3 then δl = 227µm at 200GHz spacing, 455µm for 100GHz spacing and 910µm for 50GHz ITU spacing.

The advantage of making the electrodes 102, 104 and 106 long, even though the path difference will only be around 200 to 1000µm, is that it will enable many π phase shift to be achieved by applying complementary voltages to the electrodes 104 and 106 of Figure 7. As an example for electrodes 20,000µm long, and a ±10V bias, around 8π change in relative phase can be achieved at the 1550nm wavelength of interest. The electrodes 104 and 106 can then be used to compensate for changes in temperature causing changes in group refractive index, by measuring the micro-optical photonic sub-assembly temperature and applying voltages to the electrodes 104 and 106, based upon a pre-calibrated look up table. Any stress or temperature dependent phase shifts would be calibrated out by such a procedure, provided they are not time dependent - the evidence to date is that temporal effects are a second order type effect compared to temperature.

Gallium arsenide is particularly preferred for fabricating a temperature compensated wavelength locker in accordance with the invention due to its long-term waveguide phase stability. In an alternative arrangement lithium niobate can be used but measures need to taken to prevent any long term charge build up and its consequential effect upon absolute phase i.e. due to phase drift.

Incorporation of the long waveguide lengths, with their associated long electrodes, means that the device can be calibrated and controlled over a wide temperature range.

The calibration process to create the look up table involves an arrangement as shown in Figure 8 in which 60 is a laser known to be on a desired ITU wavelength; 65 is a micro-optical photonic sub-assembly with the wavelength locker of the invention; 110 is a monitoring means that can detect the peak signal condition corresponding to the wavelength locker 100 optimally discriminating the laser wavelength; 120 is a differential output dc supply that feeds electrodes 102, 104 and 106; and 130 is a temperature measuring means which measures the temperature of the integrated structure via a temperature sensor 140. It is preferred that the temperature sensor is located adjacent to the unbalanced interferometer optical waveguides. The temperature of the monolithic optical integrated circuit is cycled and measured using 130, with a record made of the differential dc voltage required to bring the wavelength locker back in to absolute lock as indicated by 110. The results of this calibration process can then be used to create a look up table in which measured temperature produces correction voltages to be applied to the wavelength locker bias electrodes. The results of the calibration process can also be used to generate graphs of the dynamic response of the monolithic optical integrated circuit in respect to the wavelength locker temperature sensitivity such that intermediate temperature correction values can be interpolated. Monolithic optical integrated circuits have repeatable thermal characteristics such that the calibration should apply to all devices which are fabricated from the same batch.

The temperature sensor associated with 140 can be fabricated within the micro-optical photonic sub-assembly. The look up table will involve programmable read only memory and as such would be more difficult, but not impossible, to include within the monolithic optical integrated circuit. For these reasons the pre-calibrated look up table preferably forms part of the processor 97 of Figures 6, 9 and 13.

Whilst the description of the dc control has been described in relation to using differential voltages on the electrodes 104 and 106, a single voltage can be used if 104 is electrically tied to 106, but then the relative phase changes in the unbalanced waveguides 94, 92 would not be so pronounced for a given voltage.

Referring to Figure 9 there is shown a schematic representation of a tuneable laser transmitter incorporating the wavelength locker of the invention. As will be appreciated the processor 97 not only controls the tuneable laser in dependence upon the signals from detectors 93, 98 but also uses the temperature sensor 140 signal to prompt the look-up table 150 to control the dc bias 120 applied to the temperature compensated wavelength locker 100. When the tuneable laser is a SGDBR laser then the wavelength control from the processor 97 to the tuneable laser 60, can be via the phase section of the laser since only relatively small wavelength trim is required. However the invention applies equally to other forms of wavelength tuning such as for example the front and rear grating sections of the laser.

The negative feedback applied ensures that at all times the wavelength locker pulls in to the lower wavelength on the ITU grid. If a wavelength offset is required then this can

be generated by applying an incremental voltage to the wavelength locker bias so that it locks to a shifted wavelength and thus the tuneable laser is forced to also shift to this new wavelength. Such an arrangement finds particular application as part of a DWDM system controller for monitoring the DWDM network.

Whilst the wavelength locker described, which is based on a interferometer with a free spectral range equal to the ITU grid, can lock the laser to one of the ITU wavelengths it gives no information as to which ITU wavelength has been locked onto. To lock the laser to a specified ITU grid wavelength requires a measure of the actual wavelength. The wavelength locker illustrated in Figure 10 additionally includes a second unbalanced interferometer which has a very wide free spectral range and is used to give a measure to the actual wavelength. Input laser light 158, feeds a 1 to 4 directional coupler 160 that feeds waveguides 192, 194 forming a long optical path length difference interferometer, and also feeds waveguides 196, 198 forming a short optical path length difference interferometer. The long optical path length difference interferometer, which is used for wavelength locking, has bias electrodes 186 and 188 that are differentially driven against a common electrode 187 with dc voltage to compensate for temperature variations in the optical path length. Similarly, the short optical path length difference interferometer, which is used to give a measure of actual wavelength, is equipped with electrodes 183, 184 that are differentially driven against a common electrode 183 with dc voltage to compensate for temperature variations in the optical path length. Intensity detectors 172, 174 sense the light in the short path waveguides, and intensity detectors 176, 178 sense the light in the long path waveguides.

Figure 11. shows the relative plots of the intensity A, B, C and D as respectively detected by the detectors 172, 174, 176 and 178 as a function of wavelength. At line S – S which corresponds to one of the ITU grid wavelengths the absolute wavelength of the laser is given uniquely by the relative values g and h within the free spectral range of the short path interferometer. This is true provided there is only one cross over of the short path free spectral response over the entire wavelength range of interest. Clearly, the resolution of the dual interferometer increases with increasing long path, path length. The two interferometers are preferably monolithically fabricated as a single device such that they can share a common temperature sensor/compensation look up table.

It is also envisaged to connect two or more unbalanced interferometers in series with each stage providing a more accurate lock to a selected laser wavelength. As an example a three stage interferometer wavelength locker would operate as coarse wavelength lock, finer wavelength lock, finest wavelength lock with the free spectral range of each stage being elected to operate within that of the preceding stage.

The wavelength locker shown in Figure 10 can be used in a supervisory role in DWDM system as shown in Figure 12, making use of the lockers ability to make wavelength offsets. With reference to Figure 12 a plurality of optical channel modules 300 each comprise a tuneable laser source 302, that feeds a modulator 304 which is in itself a micro-optical photonic sub-assembly including a temperature compensated interferometer as described above. Each module 300 keeps itself locked to an ITU grid

wavelength using processing 308 and local dc control for the wavelength locker within 304, and feeds a combiner 310 which combines the outputs from all the modules. The output of the combiner 310, feeds an optical amplifier such as an Erbium Doped Fibre Amplifier whose output drives the network. A supervisory wavelength monitor 340 gets a tap 330, feed from the network. The supervisory monitor 340 is equipped with a temperature compensated wavelength locker such as shown in Figure 10 that is able to discriminate to absolute wavelength. The supervisory controller 340 polls round the laser wavelengths being sent to the network checking for the accuracy of the absolute wavelength of the source modules 300. When an error is detected in any wavelength a correction value is fed back from the supervisory controller 340 to the particular source module 300, where the correction value is used to modify the local interferometer wavelength locker setting within 304, to bring the local laser 302 back to the correct wavelength. The modules 300 each include memory to retain local and remote wavelength locker control information and the control settings for its respective tuneable laser.

An adaptation of the monolithic optical integrated circuit given in Figure 9, is shown in Figure 13. The temperature compensated interferometer has its input directional coupler 90 preceded by optical switches, or modulators, 382 and 384 so that the coupler can be fed with either light from the local tuneable laser 60 via 382, or from the network via 384. By taking the network feed the wavelength locker 100, can be locked to the wavelength comb existing on the network. The process of locking the wavelength locker 100, to the network ensures that the local laser 60 is locked to the network. The processor 97 detects the average offset between the two detectors 93 and 98, for the

network signals, tunes the interferometer to balance and correct free spectral range, then adjusts the local laser 60 wavelength to sit on the network comb.

The lock to the network even takes into account any wavelength offset that might exist on the network, so the micro-optical photonic sub-assembly output may now be safely added to the network in true harmony. A high accuracy would be achieved, as the device would average all of the individual wavelength offsets within the network comb. A single locker of this type can be used to control a full multi-wavelength terminal, either locking to the network or a single, local, laser with precise wavelength matching..

A similar arrangement to that shown in Figure 13 can also be used to detect incipient mode jumps in the tuneable laser. The wavelength locker 100 is set to its temperature compensated null balance for the ITU grid in use. The average signal from the detectors 93 and 98, is forced to be the same by the act of a balance being achieved. If there is incipient mode jumping in the local laser 60 a high wavelength difference signal between the detectors 93 and 98 will be detected by the processor 97. This signal may be used to trigger an alarm, or in combination with a dual or multiple interferometer system, give information to the tuneable laser controller to allow the laser to be switched to alternative, system permitted, wavelength operating away from the mode boundary problem wavelength of the local laser.

It will be appreciated that the present invention is not restricted to the specific embodiments described and that variations can be made which are within the scope of the invention. For example whilst it is preferred to fabricate the wavelength locker in

gallium arsenide it can be fabricated in other group III - V semiconductor materials such as indium phosphide (InP), silicon dioxide on silicon (SiO_2/Si), silicon dioxide on silicon dioxide (SiO_2/ SiO_2) and lithium niobate. Furthermore whilst the use of directional couplers has been described other forms of optical splitting/combining means can be used such as multimode interference devices.

CLAIMS

1. A wavelength locker for use with a wavelength tuneable laser capable of selectively producing light of fixed wavelengths, said fixed wavelengths having a substantially fixed wavelength spacing; the locker for locking the wavelength of the light to one of said fixed wavelengths and comprising: an interferometer arrangement comprising splitting means for splitting the laser light to pass along two optical waveguides and combining means for combining light from the waveguides to form at least one optical output; wherein the optical waveguides are configured to have a difference in optical path length such that the magnitude of the at least one optical output varies cyclically with wavelength and has a period which is substantially an integer multiple of said fixed wavelength spacing; and control means for controlling the laser in response to the magnitude of said optical output to lock the laser to one of said selected fixed wavelengths.

2. A wavelength locker according to Claim 1 and further comprising means for changing the refractive index of one waveguide relative to the other to change the optical path length difference.

3. A wavelength locker according to Claim 2 in which the means for changing the refractive index is operable to set the optical path difference to the integer multiple of the wavelength spacing.

4. A wavelength locker according to Claim 2 in which the means for changing the refractive index is operable to set the optical path difference such that the laser locks to a wavelength which is offset by a selected amount from one of said wavelengths.

5. A wavelength locker according to any one of Claims 2 to 4 and further comprising temperature sensing means for measuring the temperature of the waveguides and wherein the means for changing the refractive index operates in dependence on the measured temperature to maintain the optical path length difference constant.

6. A wavelength locker according to Claim 5 in which the optical waveguides comprise an electro-optic material and the means for changing the refractive index comprises one or more electrodes associated with the, or each, waveguide.

7. A wavelength locker according to any preceding claim in which the magnitude of the at least one optical output is sensed using an optical to electrical converter.

8. A wavelength locker according to Claim 7 in which the optical to electrical converter senses the magnitude of the at least one optical output by measuring a photocurrent generated by two photon absorption.

9. A wavelength locker according to any preceding claim and further comprising a second interferometer arrangement whose optical path length difference is selected such that the magnitude of its optical output varies cyclically with wavelength and wherein the period is substantially twice the wavelength range and wherein the magnitude is used to provide an indication of the wavelength.

10. A wavelength locker according to any preceding claim in which the splitting and/or combining means comprises a directional coupler.

11. A wavelength locker according to any one of Claims 1 to 9 in which the splitting and/or combining means comprises a multimode interference device.

12. A wavelength locker according to any preceding claim in which the, or each, interferometer arrangement comprises an unbalanced Mach-Zehnder interferometer.

13. A wavelength locker according to any preceding claim which is fabricated in a group III-V semiconductor material.

14. A wavelength locker according to Claim 13 which is fabricated in gallium arsenide.

15. A wavelength locker according to any preceding claim in which the combining means produces complementary optical outputs and wherein the control means controls the laser in response to the magnitude of said optical outputs.

16. A wavelength locker according to Claim 15 configured such that when the magnitude of the optical outputs are respectively a maximum and minimum this indicates that the wavelength is locked to one of said fixed wavelengths.

17. A wavelength locker according to Claim 15 configured such that when the magnitude of the optical outputs are complimentary this indicates that the wavelength is locked to one of said fixed wavelengths.

18. A wavelength locker according to any preceding claim which is monolithically integrated with the laser.

19. A wavelength locker according to Claim 18 and further comprising monolithically integrating an optical modulator for modulating the laser light.

20. A wavelength locker according to any preceding claim in which the fixed wavelengths are wavelength division multiplex channels.

21. A wavelength locker according to any preceding claim and operable to detect incipient wavelength mode jumps of the laser and further configured upon detecting a mode jump to tune and lock the laser to an alternative wavelength.

22. A wavelength locker substantially as hereinbefore described with reference to or substantially as illustrated in the accompanying drawings.

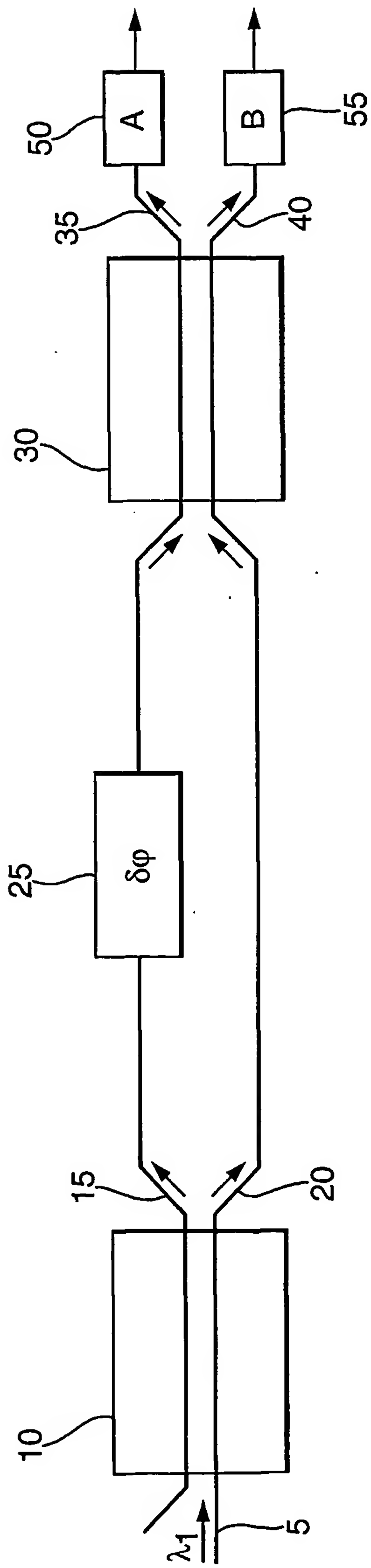


Fig.1.

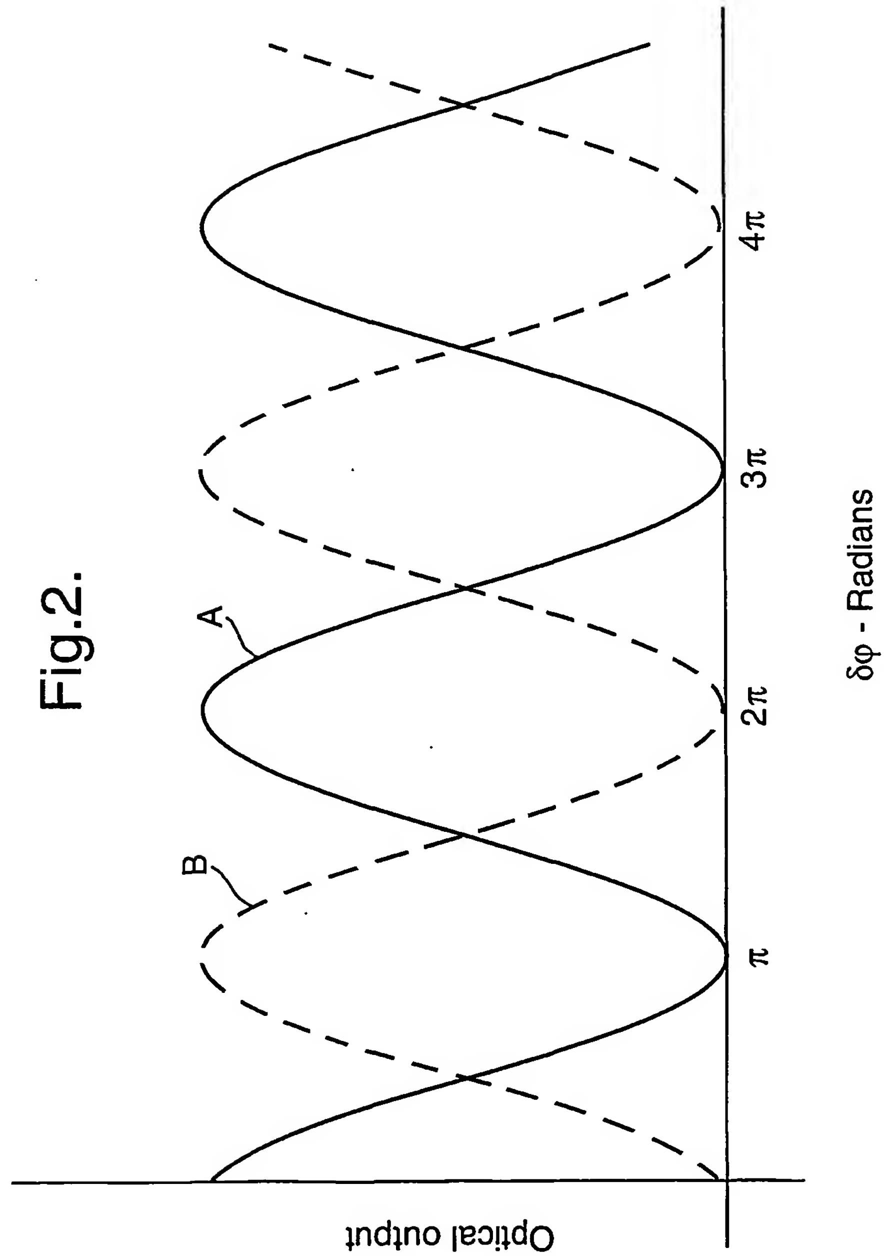
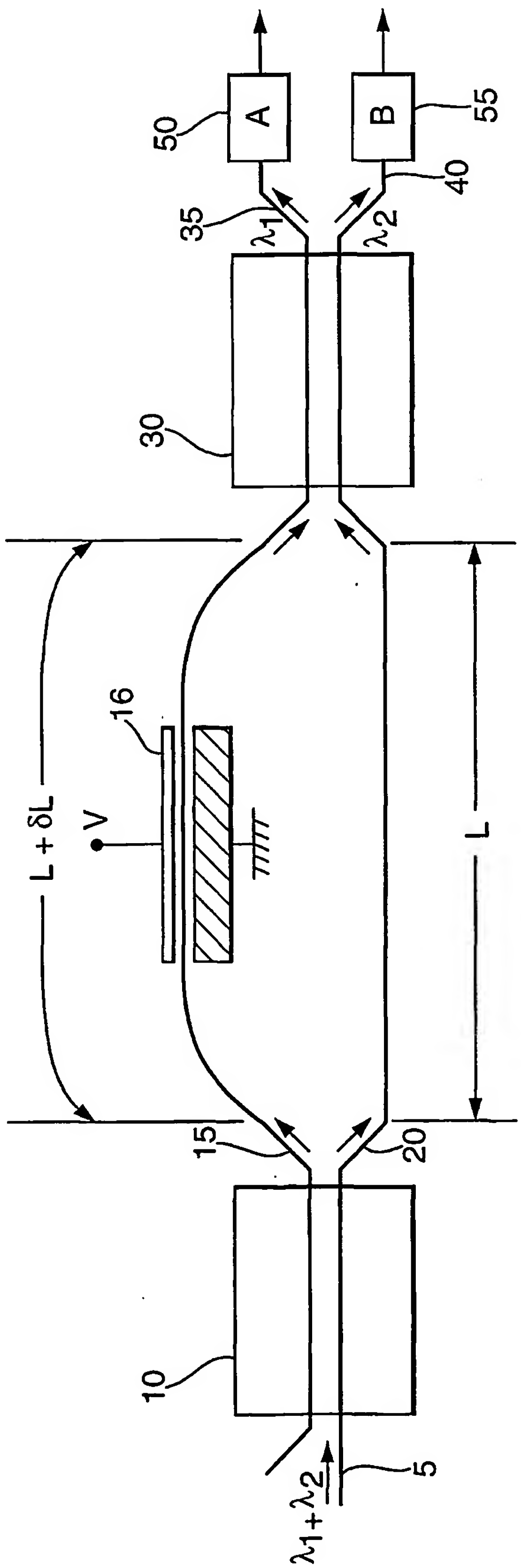


Fig.2.

Fig.3.


A
B
50
55
35
40
λ_1
λ_2
30
L + δL
L
V
16
15
20
10
5
$\lambda_1+\lambda_2$

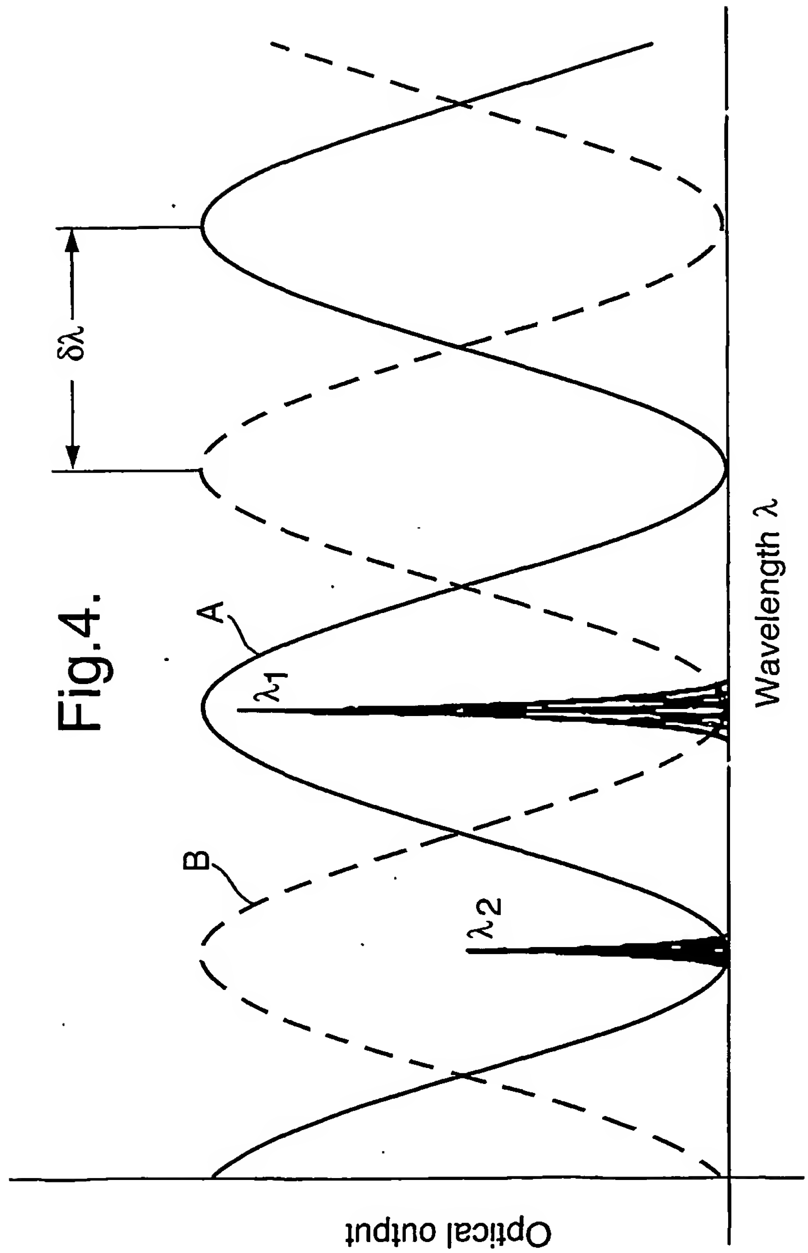
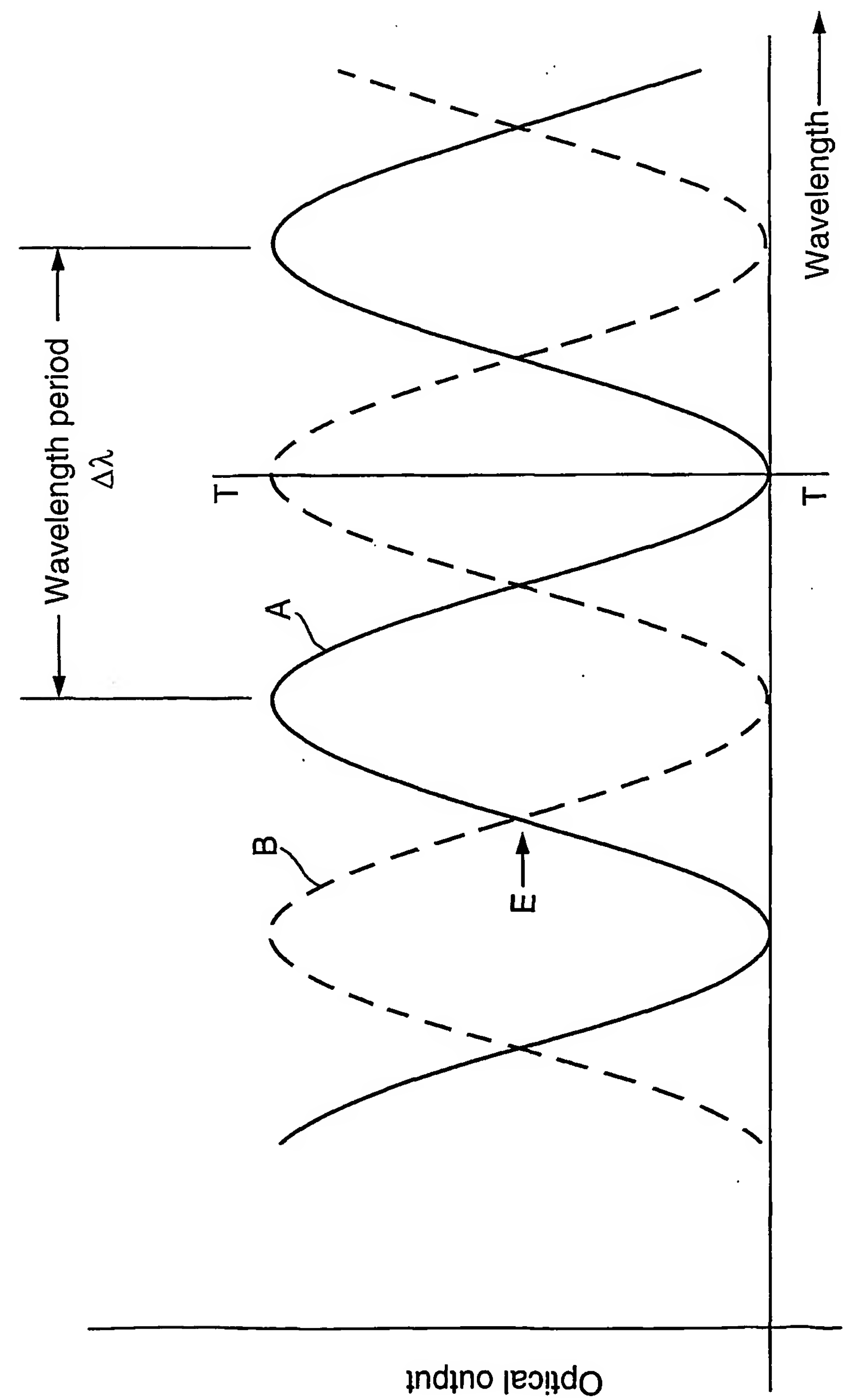


Fig.4.

Fig.5.



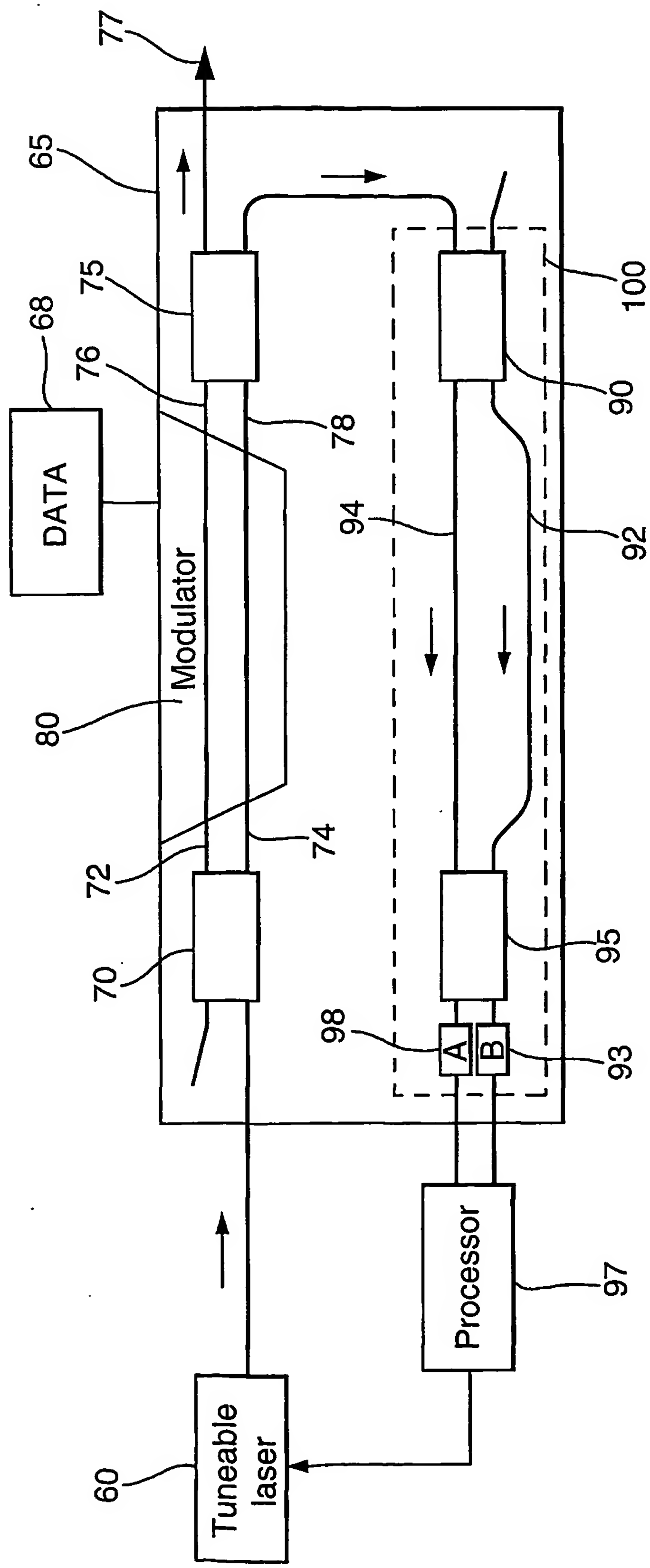

77
65
75
68
76
78
DATA
Modulator
80
94
92
90
100
72
74
70
95
98
A
B
93
Processor
97
Tuneable laser
60

Fig.6.

Fig.7.

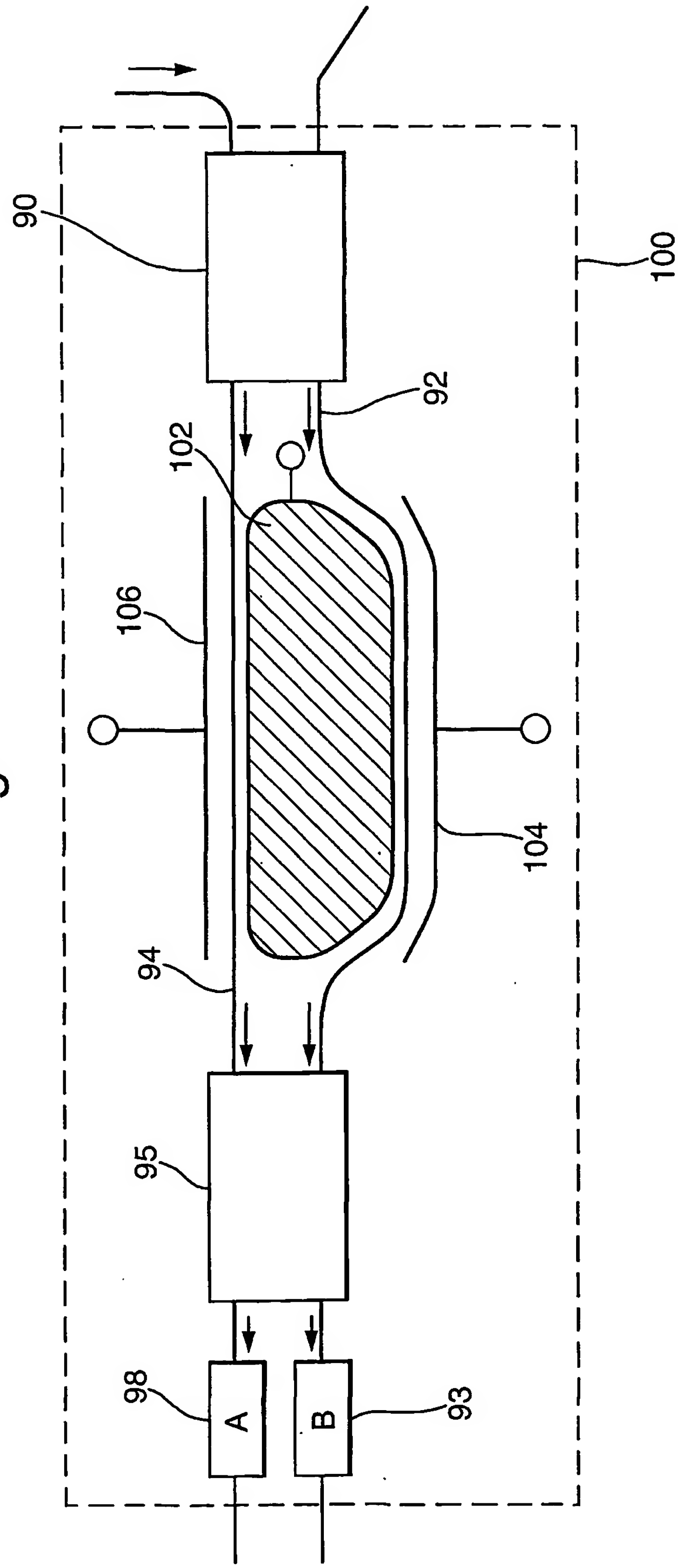


Fig.8.

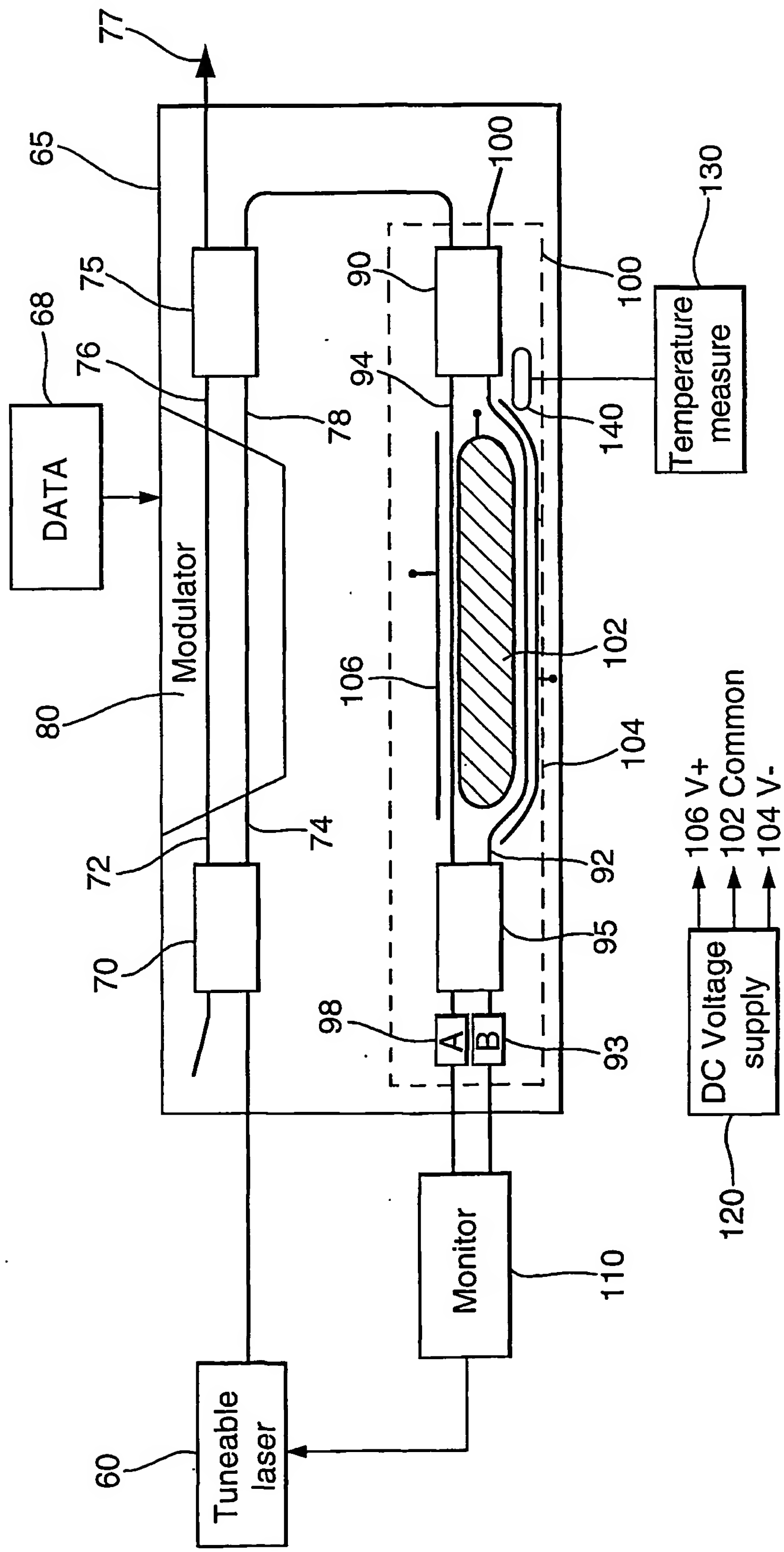

77
65
75
68
76
DATA
78
Modulator
80
72
74
70
60
Tuneable laser
Monitor
110
100
90
94
140
Temperature measure
130
106
102
104
92
95
98
A
B
93
106 V+
102 Common
104 V-
DC Voltage supply
120

Fig.9.

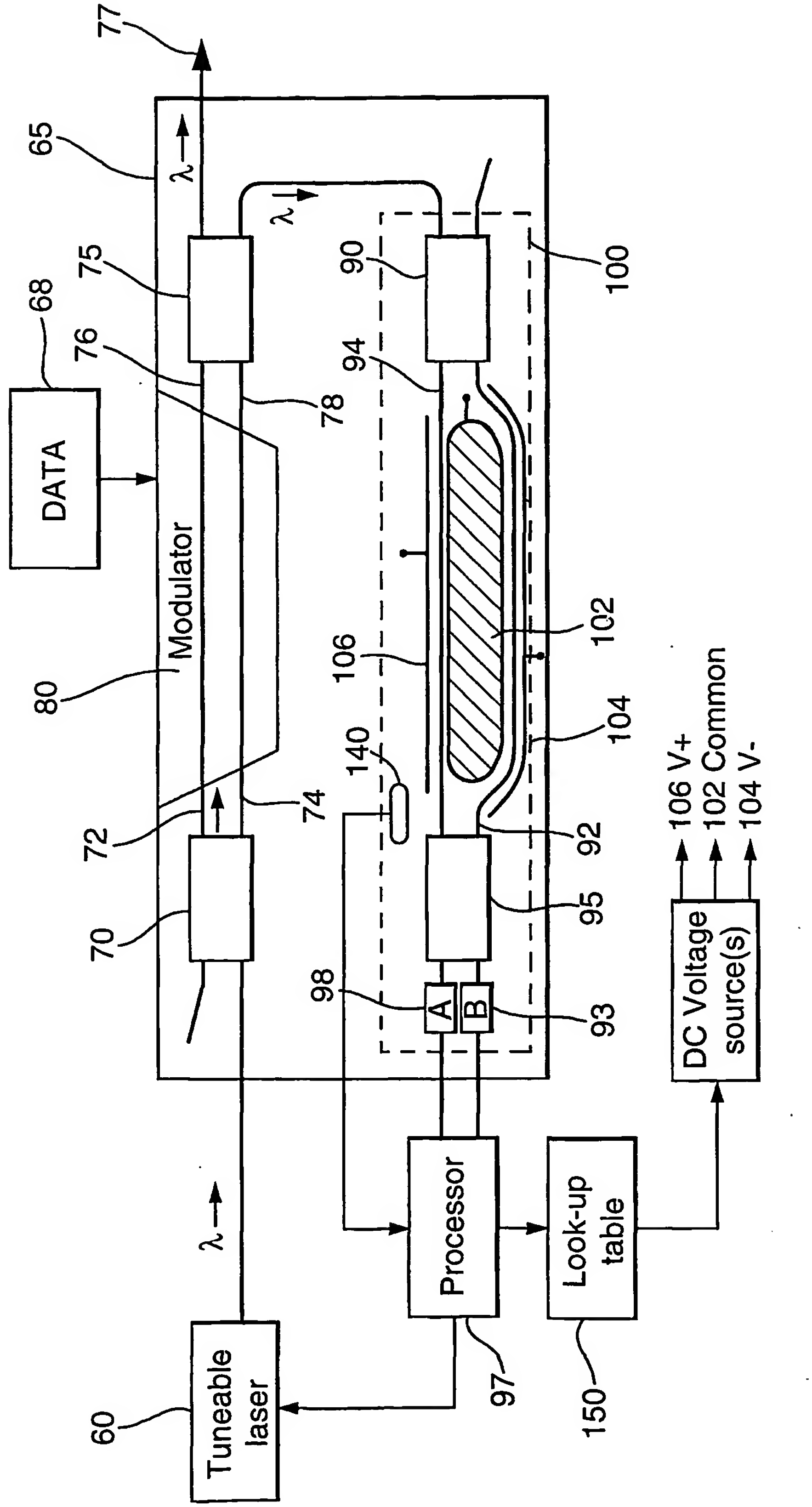

77
65
68
DATA
75
76
78
Modulator
80
λ
90
94
100
102
106
104
140
72
74
92
70
95
98
A
B
93
106 V+
102 Common
104 V-
DC Voltage source(s)
Processor
Look-up table
Tuneable laser
60
97
150

Fig.10.

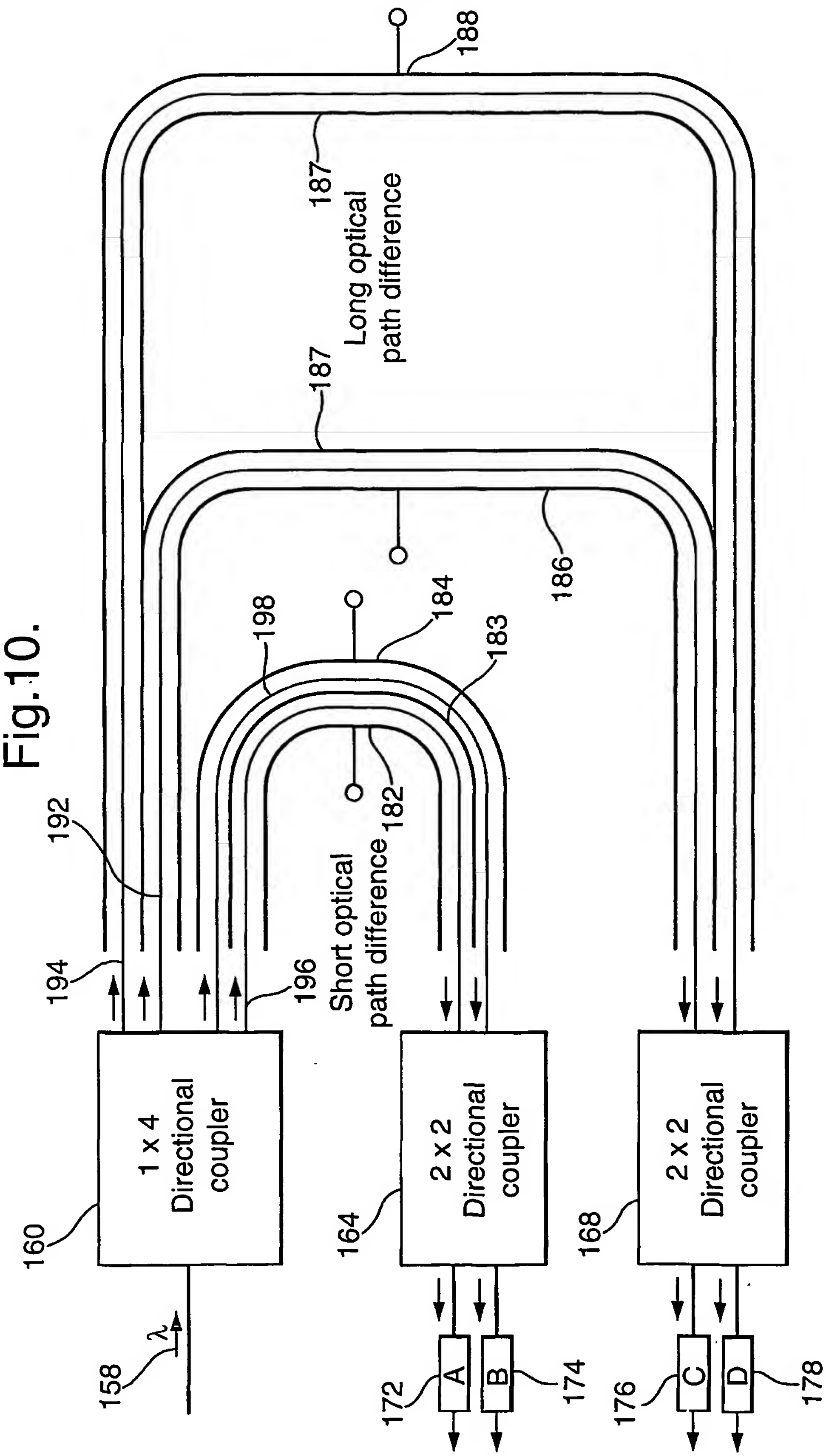
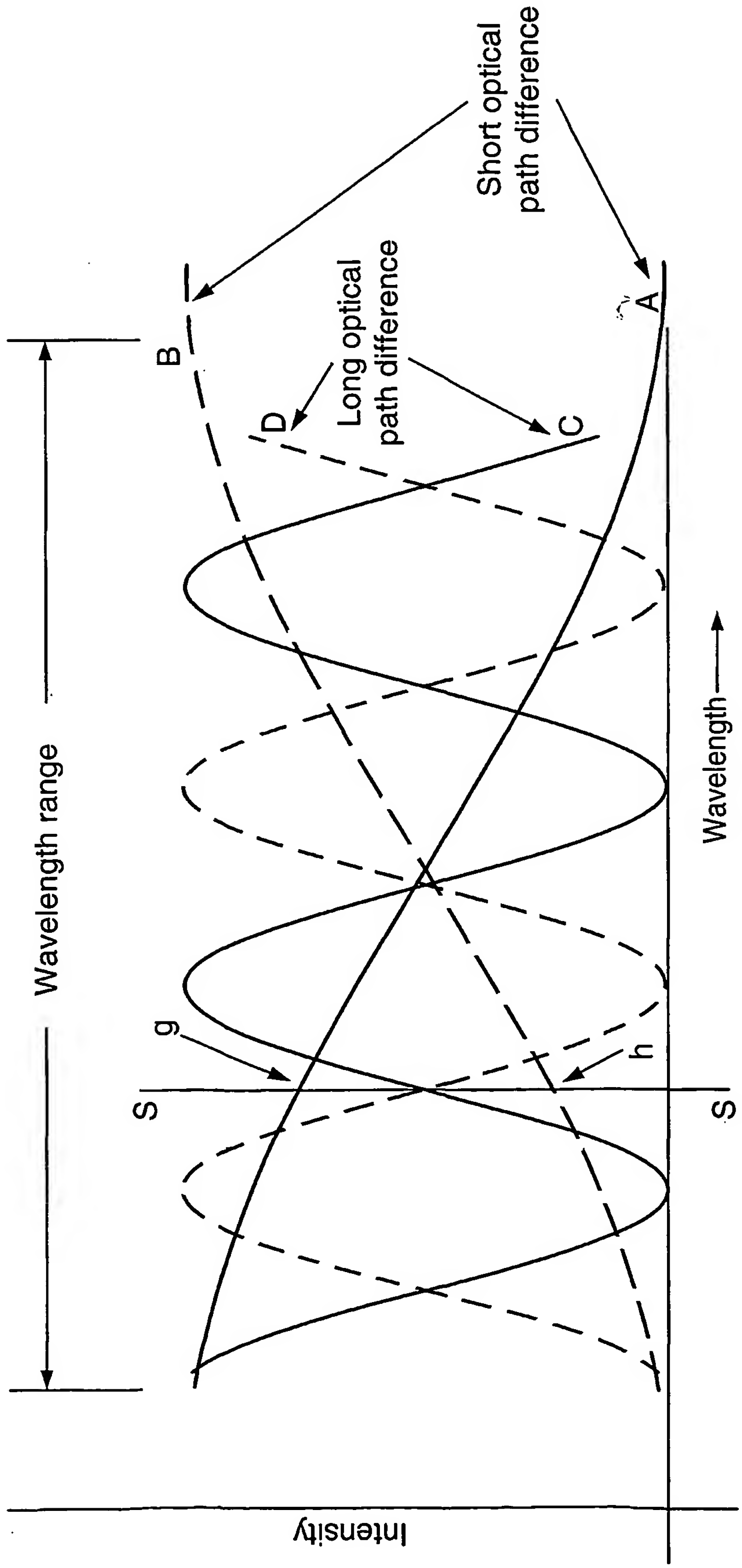

188
187
Long optical
path difference
187
186
198
184
183
182
Short optical
path difference
192
194
196
1 x 4
Directional
coupler
160
2 x 2
Directional
coupler
164
2 x 2
Directional
coupler
168
158
λ
A
B
C
D
172
174
176
178

Fig.11.


Short optical path difference
Long optical path difference
A
B
C
D
g
h
S
S
Wavelength range
Wavelength
Intensity

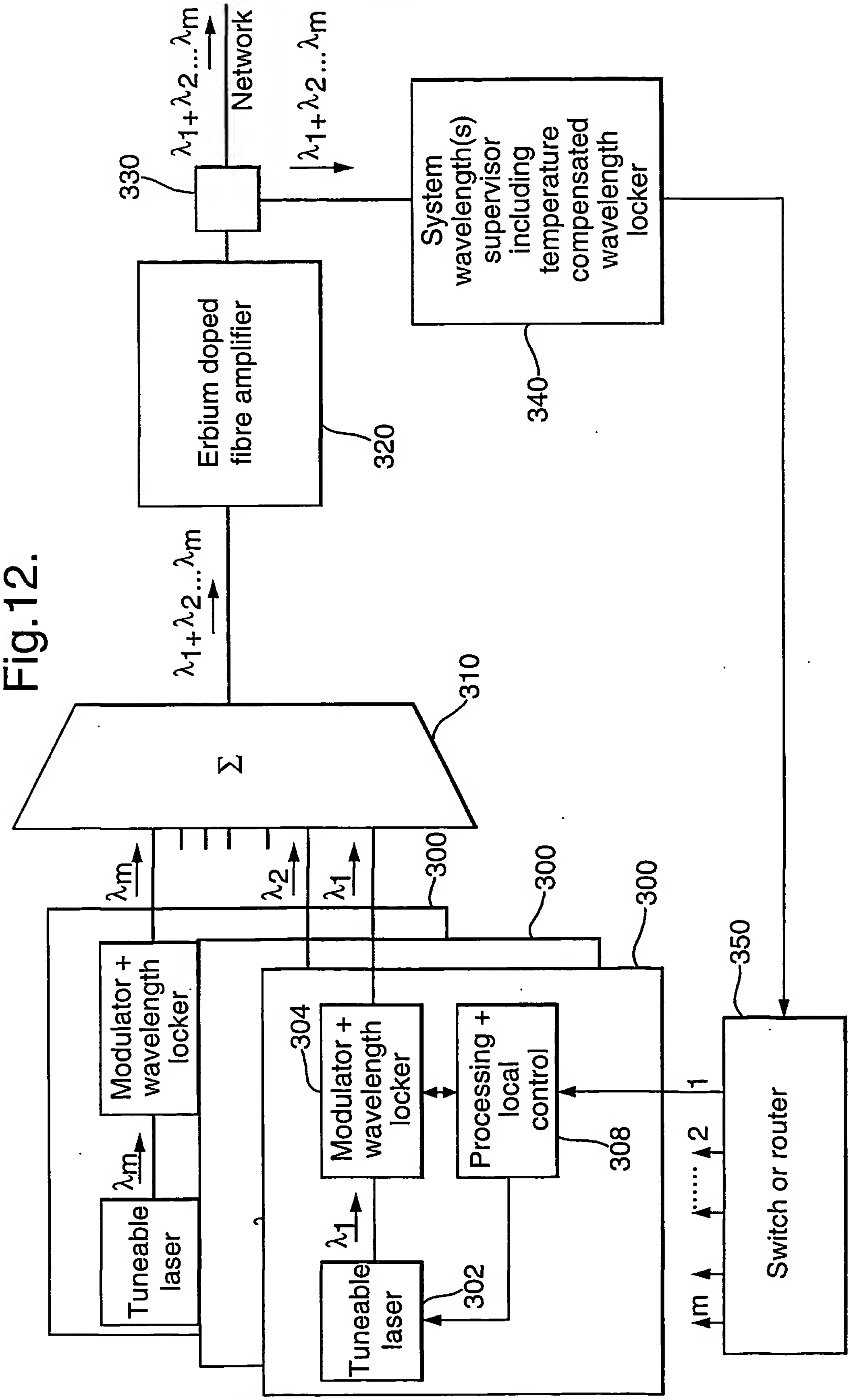
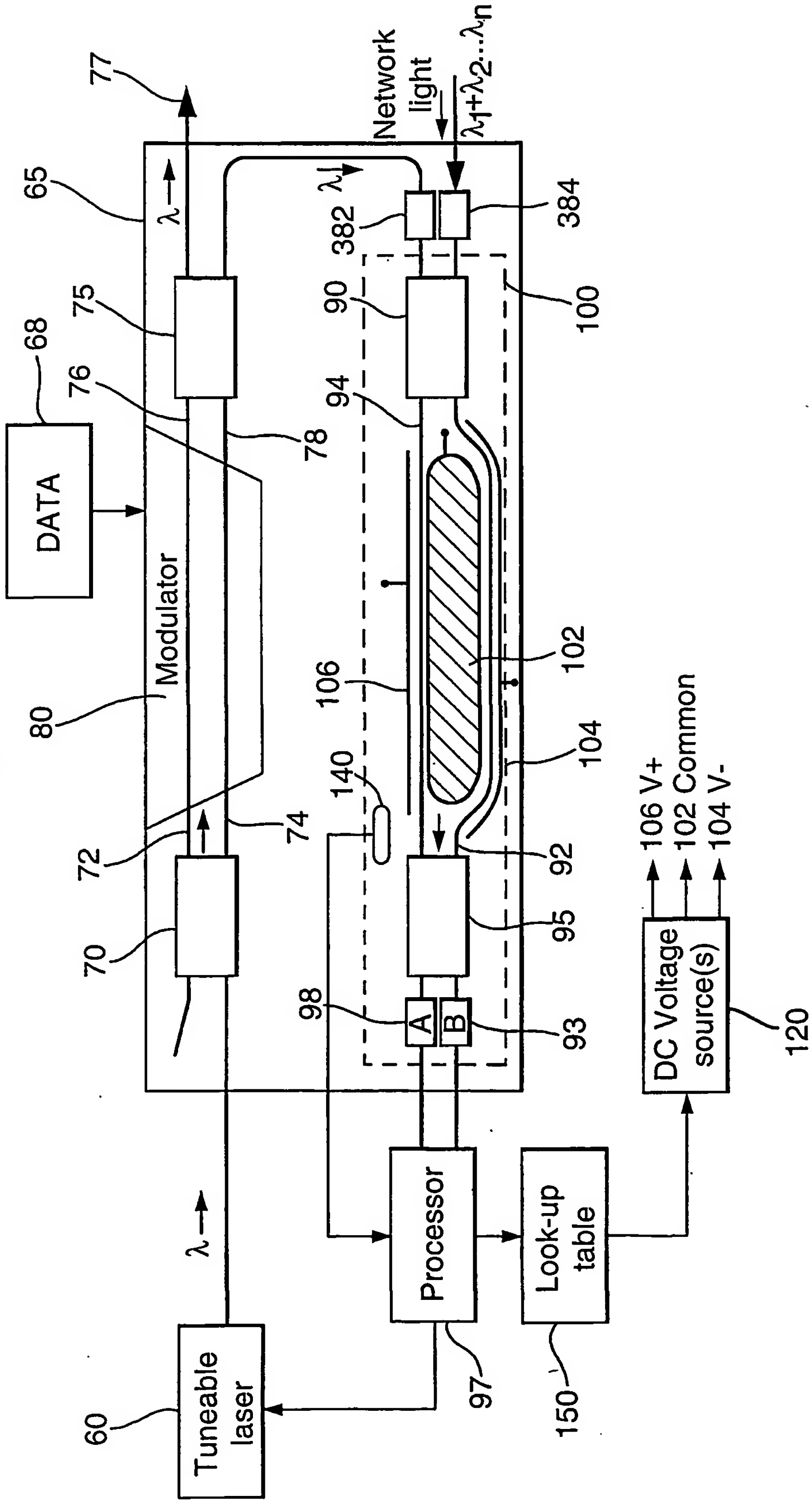

Tuneable laser
Modulator + wavelength locker
Tuneable laser
Modulator + wavelength locker
Processing + local control
Switch or router
Σ
Erbium doped fibre amplifier
System wavelength(s) supervisor including tempensated compensated wavelength locker
Network
$\lambda_1 + \lambda_2 \ldots \lambda_m$
λ_1
λ_2
λ_m
1
2
m
300
302
304
308
310
320
330
340
350

Fig.12.

Fig.13.


Network light
$\lambda_1+\lambda_2...\lambda_n$
DATA
Modulator
Tuneable laser
Processor
Look-up table
DC Voltage source(s)
106 V+
102 Common
104 V-
A
B
60
65
68
70
72
74
75
76
77
78
80
90
92
93
94
95
97
98
100
102
104
106
120
140
150
382
384

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(72) Inventor; and
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(74) Agents: **FRY, Alan, Valentine** et al.; Fry Heath & Spence, The Gables, Massetts Road, Horley, Surrey RH6 7DQ (GB).

(81) Designated States *(national)*: CA, JP, US.

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— *with international search report*

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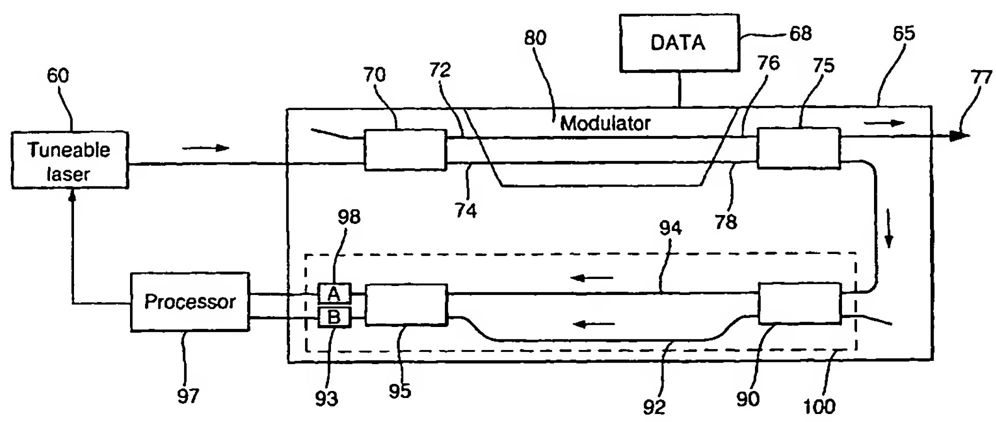
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: WAVELENGTH LOCKER



(57) Abstract: A wavelength locker (100) for use with a tuneable laser (60) capable of selectively producing light of fixed wavelengths, said fixed wavelengths having a substantially fixed wavelength spacing; the locker for locking the wavelength of the light to one of said fixed wavelengths and comprises: an interferometer arrangement comprising splitting means (90) for splitting the laser light to pass along two optical waveguides (92, 94) and combining means (95) for combining light from the waveguides to form at least one optical output (93, 98); wherein the optical waveguides are configured to have a difference in optical path length such that the magnitude of the at least one optical output varies cyclically with wavelength and has a waveguide period which is substantially an integer multiple of said fixed wavelength spacing; and control means (97) for controlling the laser in response to the magnitude of said optical output to lock the laser to one of said selected fixed wavelengths.

WO 02/039553 A3

INTERNATIONAL SEARCH REPORT

Int[redacted]pplication No
PCT/[redacted]1/04996

A. CLASSIFICATION OF SUBJECT MATTER
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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 00 49690 A (QTERA CORP) 24 August 2000 (2000-08-24) page 13, line 2 - line 5; figures 7-9 page 13, line 12 - line 16	1-4,6-8, 10-20
X	US 5 034 603 A (WILSON KEITH E) 23 July 1991 (1991-07-23) the whole document	1-8, 10-20
A	DE 40 10 823 A (STANDARD ELEKTRIK LORENZ AG) 10 October 1991 (1991-10-10) column 2, line 30 - line 32; figure 1	18,19
A	US 6 031 948 A (CHEN PETER Z) 29 February 2000 (2000-02-29) the whole document	1

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Date of the actual completion of the international search	Date of mailing of the international search report
6 November 2002	14/11/2002

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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X	EP 1 028 503 A (LUCENT TECHNOLOGIES INC) 16 August 2000 (2000-08-16) column 3, line 8 - line 12 column 3, line 32 - line 38 -----	1

INTERNATIONAL SEARCH REPORT

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Inte[illegible]pplication No
PCT/[illegible]1/04996

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
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			WO	0049690 A1	24-08-2000
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EP 1028503	A	16-08-2000	US	6445477 B1	03-09-2002
			DE	60000166 D1	20-06-2002
			EP	1028503 A2	16-08-2000
			JP	2000236135 A	29-08-2000